Ultra-Thin Compact Flexible Antenna for IoT Applications

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***Abstract*—**A CPW-fed slot monopole antenna suitable for IoT applications is designed using three different dielectric substrates: a novel flexible ceramic (ENrG's Thin E-Strate), the rigid Arlon 25N and flexible Polypropylene (PP). The required dimensions and the simulation results concerning impedance matching and radiation properties are compared. Prototypes of the optimized ultra-thin compact flexible antenna, based on the novel ENrG's Thin E-Strate, are fabricated using two different metallization techniques: electrotextile based and inkject printing. The measurement results, regarding return losses for the fabricated prototypes using both procedures are then compared and also with the simulation ones to draw some conclusions.

***Index Terms*— flexible antenna, compact antenna, ultra-thin antenna, ceramic antenna, antenna for IoT, electrotextile antenna, inkject printed antenna.**

I. INTRODUCTION

During the last decade we have witnessed a great development concerning flexible and/or miniaturized electronic devices in order to facilitate their integration in handheld equipment's and/or in clothing. The advances regarding the design and fabrication of antennas [1]-[4] based on new materials [5]-[6] and using innovative manufacturing techniques [7]-[9] are key steps towards these wearable electronics.

In the near future, a large market is foreseen for devices and emerging technologies with applications in 5G and Internet of Things (IoT). A wide variety of frequency bands are considered for these new standards definitions, both under 6GHz and at much upper frequencies (such as 24GHz, 28-29GHz, 60GHz, and even higher values), with emphasis on ISM bands. Focusing on IoT, the frequencies traditionally allocated for WLAN (around 2.4GHz, 3.6GHz, 4.9GHz, 5GHz, 5.9GHz) and wireless sensor networks communications (ZigBee, Bluetooth, RFID, NFC,….) mostly around 2.45GHz are preferred [5]-[6], [10]-[11], due to the lower losses and the know-how concerning not only the channel characterization, but also the previously developed electronics. In addition, frequencies below 1GHz such as 900MHz and 700MHz are also considered for some 5G applications although frequency re-farming is pending in some countries. Taking into account these perspectives, the design of flexible and/or miniaturized antennas suitable for integration in next generation devices is of great interest, at the same time that challenging.

This work aims at designing and manufacturing an ultra-thin flexible antenna based on a novel ceramic material, ENrG's Thin E-Strate, for IoT applications at frequencies around 2.7GHz and 5.8GHz (covering several of the intended bands), and compare its dimensions and performance (concerning matching and radiation properties) with the ones obtained using conventional rigid Arlon 25N dielectric and flexible polypropylene substrates.

This contribution is organized as follows: first the characteristics of the novel flexible ceramic material are described, as well as the ones of the conventional Arlon 25N and polypropylene. Then, the CPW-fed antenna design based on the three materials is presented and the obtained results are compared based on simulation. Prototypes of the designed antenna are fabricated using two different metallization techniques and their performance is compared with the simulation in terms of return losses. Finally some conclusions are drawn.

II. DIELECTRIC SUBSTRATES FOR THE DESIGN OF THE ANTENNA

A. Ultra-Thin Flexible Ceramic material

ENrG's Thin E-Strate is an ultra-thin, flexible, ceramic substrate which has properties for developing higher performance products than those based on traditionally available materials. The most remarkable properties are: flexible, mechanically robust, light-weight ceramic; high temperature tolerance, high thermal shock tolerance, impermeable to gases and moisture; chemically inert (in most harsh chemical environments; easily coated with conductive metals) and high wear and abrasion resistances.

From the electromagnetic point of view, Thin E-Strate is a Zirconia based ceramic that exhibits a relative dielectric permittivity ε_r= 26 at 100 KHz and ε_r= 28 at 10GHz and a loss tangent tanδ=0.0048 at 2.6GHz. It is available in sheet, wafer or ribbon formats with thicknesses of 20 and 40 microns. However, taking into account further characterization tasks at the intended frequencies of operation for the antenna designed in this work, and the fabrication methodologies to be used, the following values will be considered in simulation: ε_r= 22, tanδ=0.001 and h=0.04mm.

According to the available technical information, Thin E-Strate can offer new options in the development of harsh environment sensors, power electronics circuit boards, LEDs and luminaires, contoured circuit boards for space and aviation, micro-batteries and thin-film photovoltaic cells, to name a few potential applications. Thus, it opens the path to smaller, lighter products. However, the possibility of using this novel flexible ceramic material for antennas has not been explored yet.

B. Alternative conventional materials

As mentioned in the introduction, two dielectric substrates more conventionally used for antennas fabrication are going to be considered for the IoT antenna design.

One is rigid, the Arlon 25N with relative dielectric permittivity ε_r=3.38, loss tangent tanδ=0.0025 and thickness h=0.812mm (this material could also be replaced by Rogers 4003C with very similar electromagnetic characteristics while using the same thickness).

The other is flexible polypropylene (PP), with ε_r=2.26, loss tangent tanδ=0.002 and thickness h=0.45mm, which has been previously characterized and used for antennas' fabrication at 2.45GHz and 5.8GHz frequencies by members of this research team [12] and also used by other authors.

III. CPW-FED SLOT MONOPOLE ANTENNA DESIGN

Coplanar-Waveguide-feeding (CPW-feeding) has been chosen, since it provides much wider bandwidth than microstrip feeding, while it requires metallizing only one layer [12]. The reference impedance is 50Ω.

A. Antenna geometry and optimized dimensions

For the design of the feeding line, with a width W_L and gap g, not only the 50Ω impedance but also the dimensions of commercially available connectors have been taken into account.

Fig.1 shows the geometry of the monopole antenna. The radiating slot is defined by surrounding a hexagonal shaped patch, arising from the CPW-feeding line, with metallic strips connected to both sides of the ground plane.

The dimensions of the antenna have been optimized, through FEM based 3D electromagnetic simulation using commercial software, so that it is properly matched at the intended IoT bands (around 2.75GHz and 5.8GHz) for the three dielectric substrates (ENrG's Thin E-Strate, Arlon 25N and polypropylene (PP)). The aim is not so much to design the best possible antenna, but to design a compact antenna that properly covers the intended bands and to compare the size and performance with the three materials, to study the possibilities of the novel ceramic substrate for antenna`s applications. The dimensions obtained for the optimized antenna design, in terms of impedance matching, based on the different materials are detailed in TABLE I

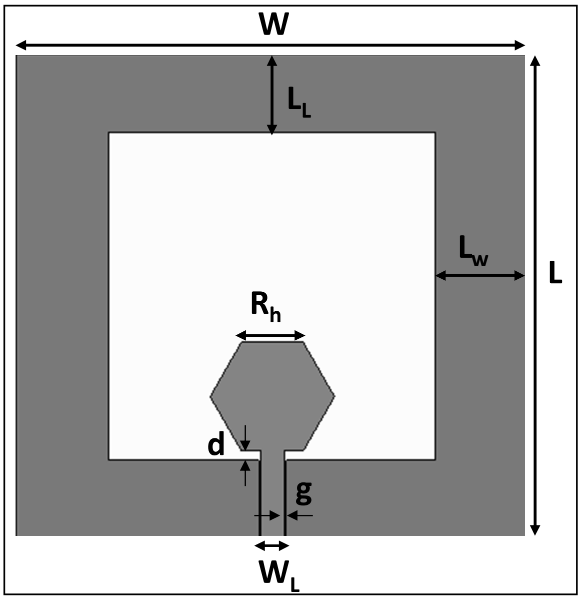

Fig. 1. *Geometry of the CPW-fed slot monopole antenna*

Increasing W improves the matching in the upper frequency band whereas increasing L does it in the lower band while shifting-down the upper resonance. A higher value of Rh decreases the upper resonance frequency, so that if its value is too low there is only one resonance in the intended frequency range. A higher d value improves the matching, especially for the upper band. L_W mainly influences the matching of the lower band whereas L_L varies the matching while shifting both frequency bands, so that a trade-off has to be adopted.

According to TABLE I the total size of the optimized CPW-fed slot monopole antenna based on ENrG's Thin E-Strate is 40.92cm^2**,** whereas for both Arlon 25N and PP is 48.3cm^2. Thus, using the novel Thin E-Strate substrate leads to a 15.28% size reduction. Furthermore, this new substrate is 20 times thinner than Arlon 25N and 11.25 times thinner than the PP. Therefore, the antenna on the novel flexible substrate is, not only smaller than on the rigid Arlon 25N and the flexible PP, but also much thinner.

TABLE I

Subs-trate	Dimensions (mm)								
	W	L	h	W_L	g	d	R_h	L_L	L_W
Thin E-Strate	66	62	0.04	3	0.26	1.2	8	10	12.0
Arlon 25N	70	69	0.80	4	0.23	1.5	7	13	14.5
PP	70	69	0.45	4	0.15	1.5	8	12	13.0

B. Antenna matching

From return loss simulation results shown in Fig. 2, it can be observed that the CPW-fed slot monopole antenna is well matched at the intended IoT bands for the three dielectric substrates under consideration and for the corresponding dimensions included in TABLE I.

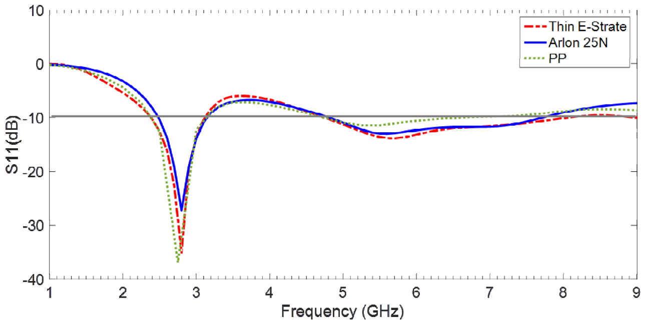

Fig. 2. *Return loss simulation results for the CPW-fed slot monopole antenna based on ENrG's Thin E-Strate, Arlon 25N and polypropylene (PP) substrates*

The flexible PP provides better impedance matching than the Arlon 25N for the lower frequency band around 2.7GHz, whereas for the upper band around 5.8GHz the Arlon 25N renders better matching than the PP. Moreover the Thin E-Strate allows very good impedance matching for both frequency bands. The antenna based on ENrG's Thin E-Strate is better matched than one based on the Arlon 25N for both bands, is at a similar level than for a design based on the PP for the lower band and much better for the upper band.

The specific operation frequencies and bandwidths obtained in simulation for the CPW-fed slot monopole antenna based on the three dielectrics are indicated in TABLE II. It can be observed that the use of the novel ENrG's Thin E-Strate makes possible obtaining the same bandwidth for the lower band than with the PP (27% vs 23% obtained for the Arlon 25N) and the widest bandwidth for the upper band (51% vs 47% for the Arlon 25N and 33% for the PP).

These results are very remarkable taking into consideration that the flexible ENrG's Thin E-Strate is more than ten times thinner than the flexible PP and 20 times thinner than the rigid Arlon 25N, while reducing the whole antenna size more than 15% compared to both of them.

TABLE II

Subs-trate	Lower band				Upper band			
	Freq (GHz)		BW		Freq (GHz)		BW	
	f_{Low}	f_{Up}	Total (MHz)	%	f_{Low}	f_{Up}	Total (MHz)	%
Thin E-Strate	2.383	3.118	735	27	4.754	8.013	3259	51
Arlon 25N	2.490	3.151	661	23	4.808	7.739	2930	47
PP	2.385	3.136	751	27	4.737	6.620	1883	33

C. *Radiation properties of the antenna*

The radiation properties of the CPW-fed slot monopole antenna have been analyzed in simulation for the three substrates under consideration.

TABLE III indicates the results obtained concerning the peak-realized gain G(dB), the directivity D(dB) and the radiation efficiency η(%), for several frequencies included in both the lower and the upper bands.

TABLE III

Freq. (GHz)	Thin E-Strate			Arlon 25N			PP		
	G (dB)	D (dB)	η (%)	G (dB)	D (dB)	η (%)	G (dB)	D (dB)	η (%)
2.45	4.10	4.46	92	3.87	4.48	87	4.14	4.51	92
2.75	4.52	4.56	99	4.54	4.61	98	4.57	4.61	99
3.00	4.27	4.49	95	4.55	4.78	95	4.54	4.80	94
5.00	4.09	4.47	92	4.33	4.72	91	4.63	4.97	92
5.80	5.19	5.40	95	5.83	6.06	95	5.44	5.75	93
6.50	5.87	6.16	94	6.62	6.88	94	6.36	6.75	91
7.00	6.60	6.91	93	7.49	7.72	95	7.21	7.60	91
7.50	7.21	7.54	93	7.90	8.16	94	7.75	8.17	91

It can be observed that the antenna behaves in a very similar way for the three dielectrics. The gain and the directivity are slightly higher for the Arlon 25N and the PP. For most WLAN and IoT applications omnidirectional antennas are preferred, so that the directivity is not the parameter to be enhanced. However, the radiation efficiency is the key parameter and the challenging one to be preserved when reducing the antenna size. It can be highlighted that with ENrG's Thin E-Strate the radiation efficiency is slightly improved for the lower band compared to the Arlon 25N and for the upper band compared to the PP.

The radiation patterns of the CPW-fed slot monopole antenna have been obtained in simulation for the 2.7GHz and 5.8GHz frequencies. The results in both 3D and the corresponding cuts for Phi=0º (H-plane) and Phi=90º (E-plane) are depicted in Fig. 3. As expected, the antenna exhibits a monopole like radiation pattern, quite omnidirectional for the H-plane at both frequency bands.

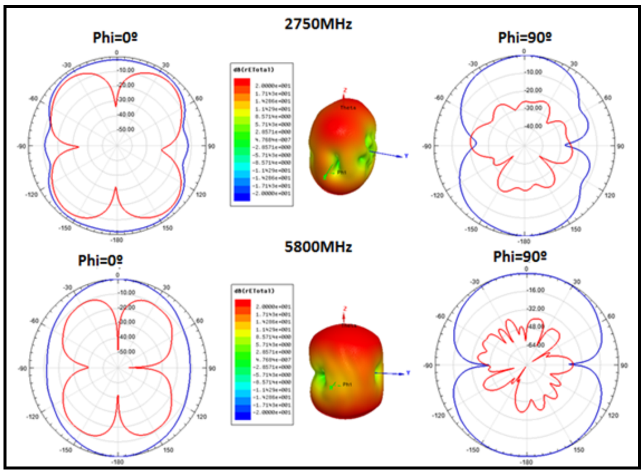

Fig. 3. Radiation patterns in simulation for the CPW-fed monopole antenna on ENrG's Thin E-Strate at 2.75GHz and 5.8GHz. *The blue curves are for copolarization (CP) and the red ones for crosspolarization (XP).*

IV. FABRICATED ANTENNA ON NOVEL MATERIAL

In view of the simulation results, prototypes of the CPW-fed slot monopole based on the novel ceramic ENrG's Thin E-Strate have been fabricated.

A. *Fabrication of the antenna prototypes*

The conductive parts of the antenna geometry for the first prototype shown in Fig. 4a) and c), have been realized with

Shieldit Super electrotextile, which incorporates a hot melt adhesive backing, and using laser micrormachinning with the LPKF Protolaser-S machine.

For the second prototype shown in Fig. 4b) a silver-based conductive ink (GenesInk Smart Ink S-CS01130) has been used, being printed with the Dimatix DMP-2831 materials printing system using 10pl cartridges. The ceramic substrate was fixed to the printing area using vacuum for ensuring flatness and avoiding any movement during the printing process. After printing, a 20 minutes long thermal process in an oven at 140ºC was needed for curing the ink and achieving good electrical properties. Once the ink is cured, the connector was placed and fixed using Gwent Group C2131014D3 conductive adhesive, a paste developed for screen printing with good adhesion. Once the connector is placed in the adequate position a thermal process has been carried out (120ºC, 10 minutes).

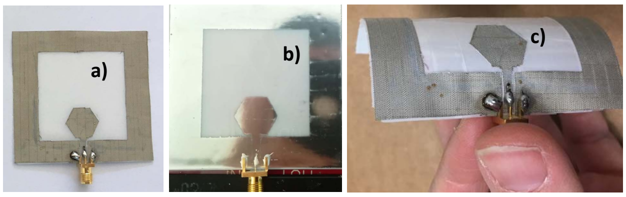

Fig. 4. *Manufactured prototypes of the antenna on ENrG's Thin E-Strate using electrotextile flat a) and bent c) and using silver conductive ink b) .*

B. *Experimental characterization based on return losses*

Fig. 5 shows the return losses results obtained in simulation and measurement for the fabricated prototypes with electrotextile and inkject printing. Proper matching is obtained in both cases, getting better agreement compared to simulation for the upper band. The prototypes are suitable for 2.48-2.94GHz and 4.87-6.82GHz IoT frequencies considering the worst case of a first attempt with inkjet printing. Wider bandwidths, 2.39-3.68GHz and 4.80-6.95GHz are obtained using electrotextile, although both techniques could be further improved.

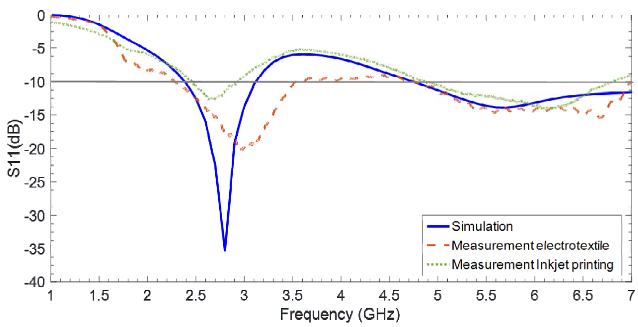

Fig. 5. *Return losses for the CPW-fed slot monopole antenna on ENrG's Thin E-Strate in simulation and measurement using electrotextile and inkjet printing as metallization in the fabrication process.*

V. CONCLUSIONS

An ultra-thin compact flexible CPW-fed slot monopole antenna, suitable for IoT applications around 2.75GHz and 5.8GHz, has been designed using ENrG's Thin E-Strate. This novel ceramic dielectric provides, respectively 20 times and 11.25 times thinner antenna compared to Arlon 25N and flexible PP, while resulting in more than 15% size reduction.

Antenna prototypes on ENrG's Thin E-Strate have been fabricated using two metallization techniques and characterized in terms of return losses with proper results.

ACKNOWLEDGMENT

Special thanks to Kathy Olenick and also to Tim Curry from ENrG Inc. for supplying the ENrG's Thin E-Strate samples and providing useful information about it. This work has been supported by the Gobierno del Principado de Asturias under Project GRUPIN18-000191 and under grant BP16024.

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